# Monitoring the Transportation Infrastructure with Satellite-Based Interferometric Synthetic Aperture Radar (InSAR)

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Geohazards Impacting Transportation in Appalachia
Interstate Technical Group on Abandoned Underground Mines

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# Overview of Presentation

- Problem Statement
- Relevance to transportation
- Technology and Data Collection
- Analysis method
- Results and Validation
- Conclusion and future work

# Project: Problem Statement

Can InSAR technology be used to detect and monitor ground features of interest to the transportation community?

In particular, can leading edge satellite-based interferometric techniques provide a proactive rather than reactive approach to potentially hazardous phenomena such as **sinkholes**, landslides and bridge displacement?

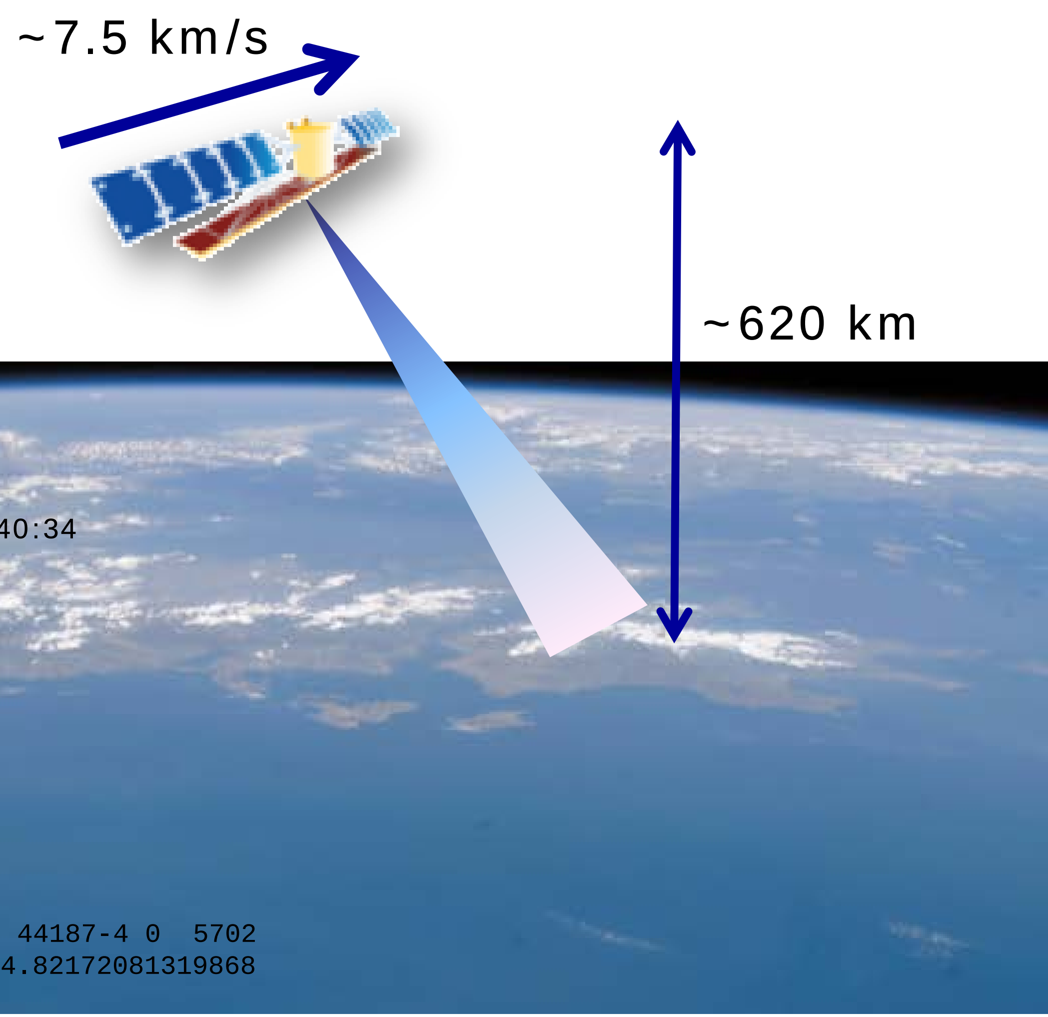
(InSAR: interferometric synthetic aperture radar)

# Relevance to Transportation

- Increased Safety:
  - Increase safety of the traveling public and reduce the liability exposure to a DOT
- Reduced inconvenience for public:
  - Reduce delays associated with highway closure
- Reduced Costs (VDOT):
  - Emergency costs:
    - Typically 2 to 5 times higher than standard maintenance
  - High individual costs:
    - Minimum cost per sinkhole: $25k
  - High aggregate costs:
    - About $1.2M/year for sinkholes and landslide in central VA

# InSAR Technology: Satellite

- Active System
- Not affected by weather

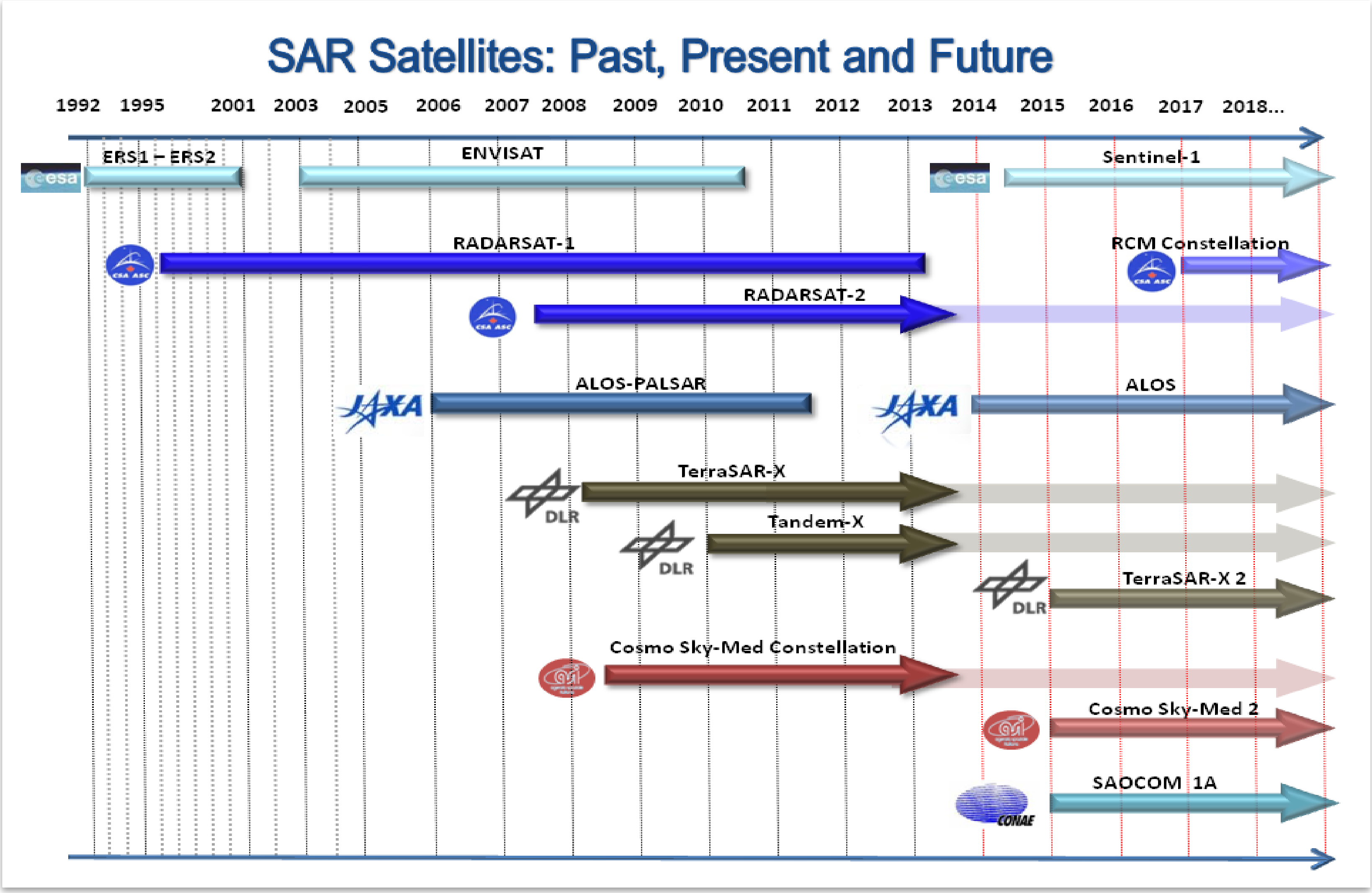



**COSMO-SkyMed1**

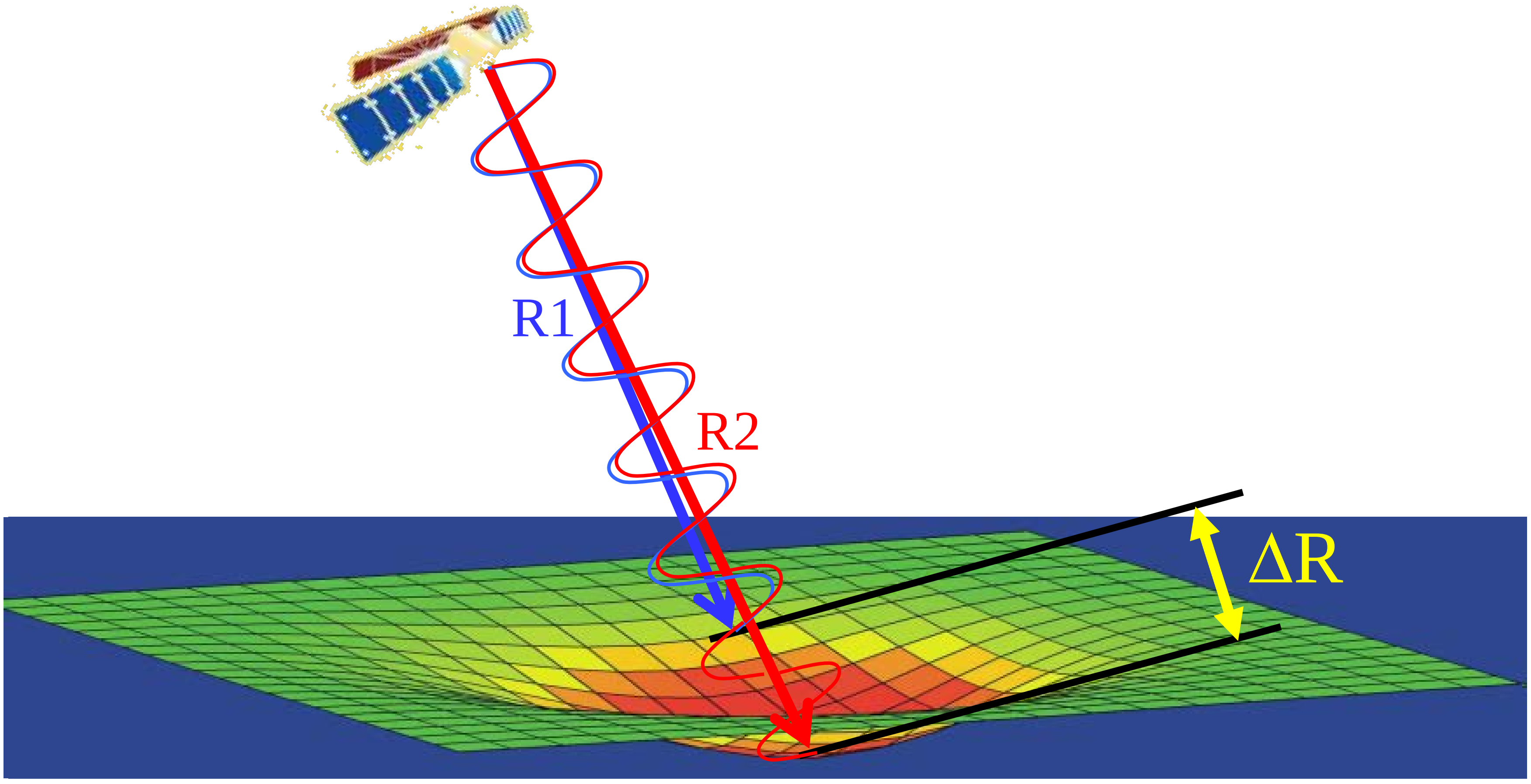
| | |
|---|---|
| Epoch (UTC): | 06 May 2013 12:40:34 |
| Eccentricity: | 0.0001324 |
| Inclination: | 97.8736° |
| Perigee height: | 621 km |
| Apogee height: | 623 km |
| Right ascension of ascending node: | 312.4119° |
| Argument of perigee: | 82.6105° |
| Revolutions per day: | 14.82172081 |
| Mean anomaly at epoch: | 277.5294° |
| Orbit number at epoch: | 31986 |

```
1 31598U 07023A   13126.52817318  .00000300  00000-0  44187-4 0  5702
2 31598 097.8736 312.4119 0001324 082.6105 277.5294 14.82172081319868
```

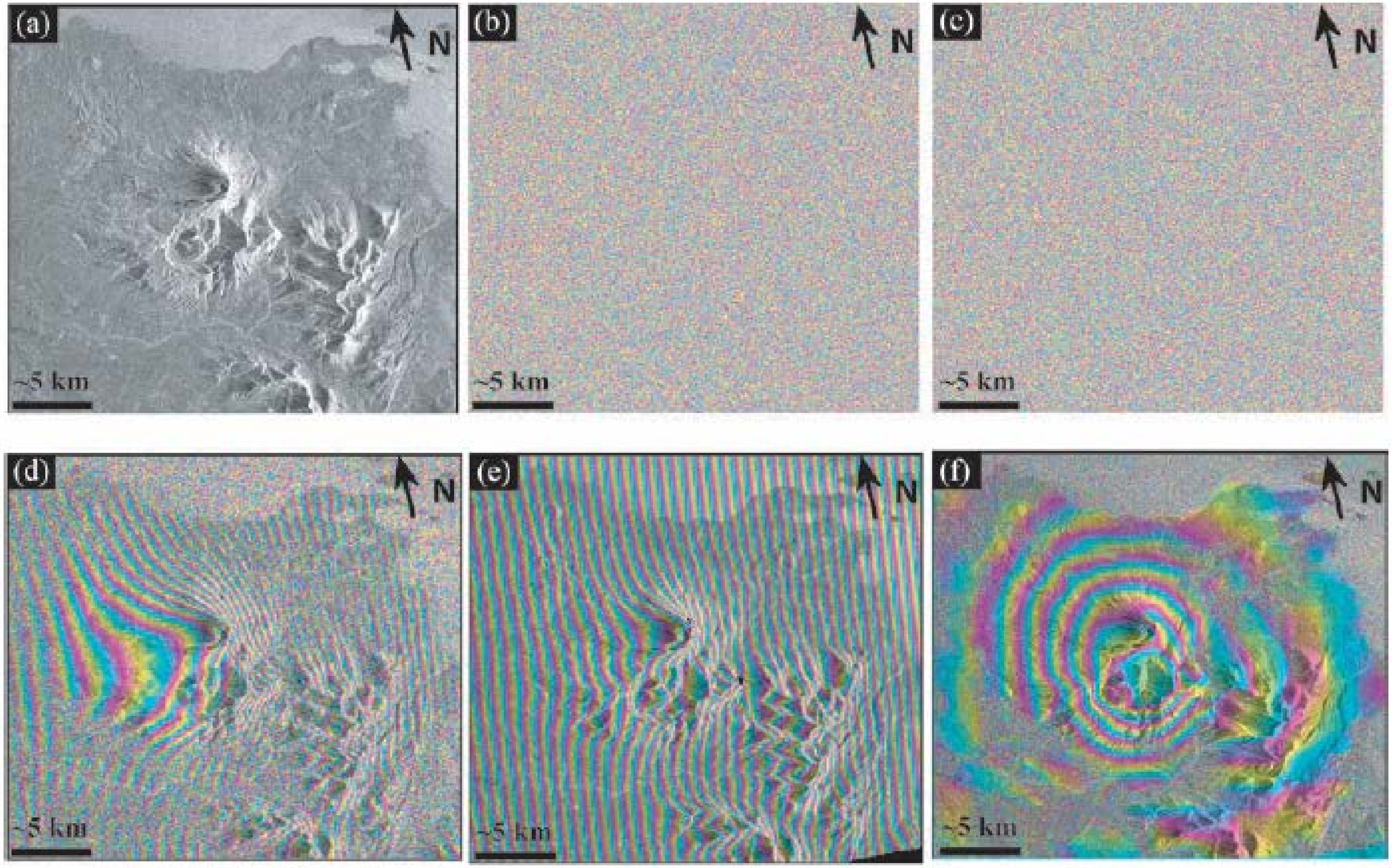
# InSAR Technology: Satellite



# InSAR Technology: Theory



# Differential InSAR




*Z. Lu, "InSAR imaging of volcanic deformation over cloud-prone areas - aleutian islands," Photogrammetric Engineering & Remote Sensing, vol. 73, no. 3, pp. 245–257, Mar. 2007.*

# InSAR Technology: Products

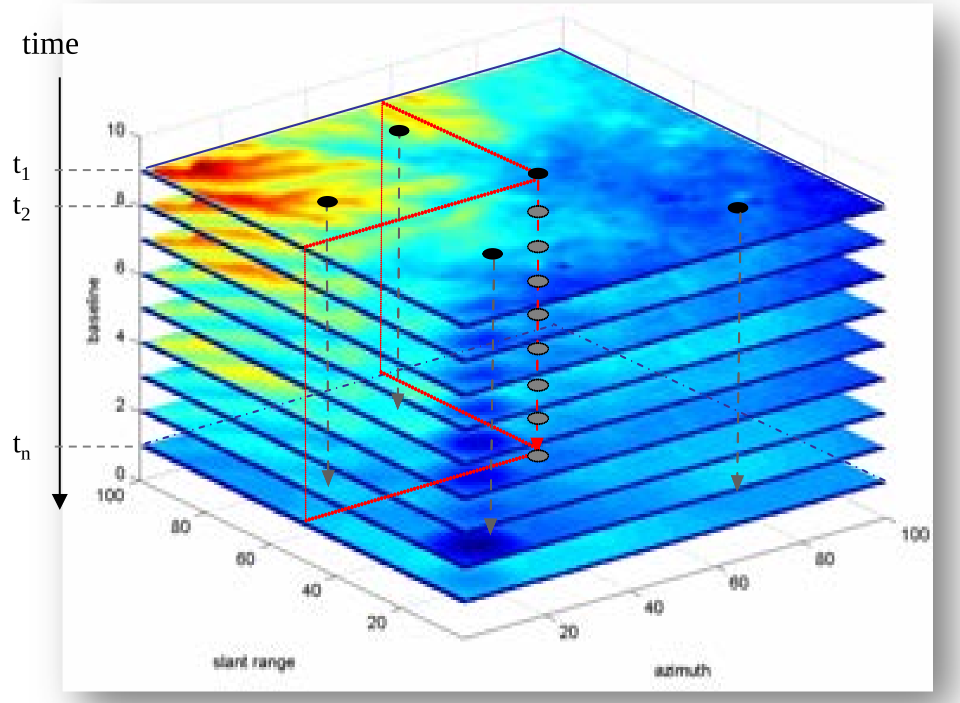
## PSInSAR™ uses at least 15 images

- only stable radar targets (PS) on the ground are used for measurements

- atmospheric effects removed

  ➔ measurements have millimeter accuracy

- now have a history of motion



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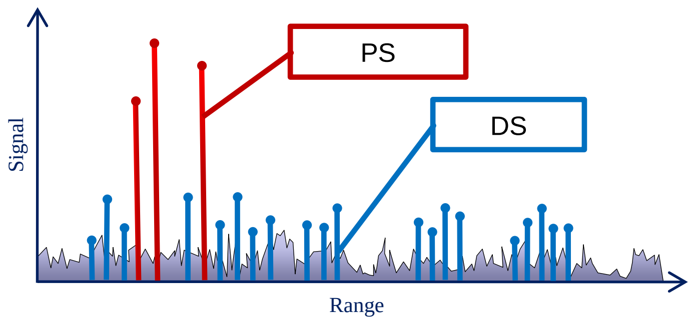
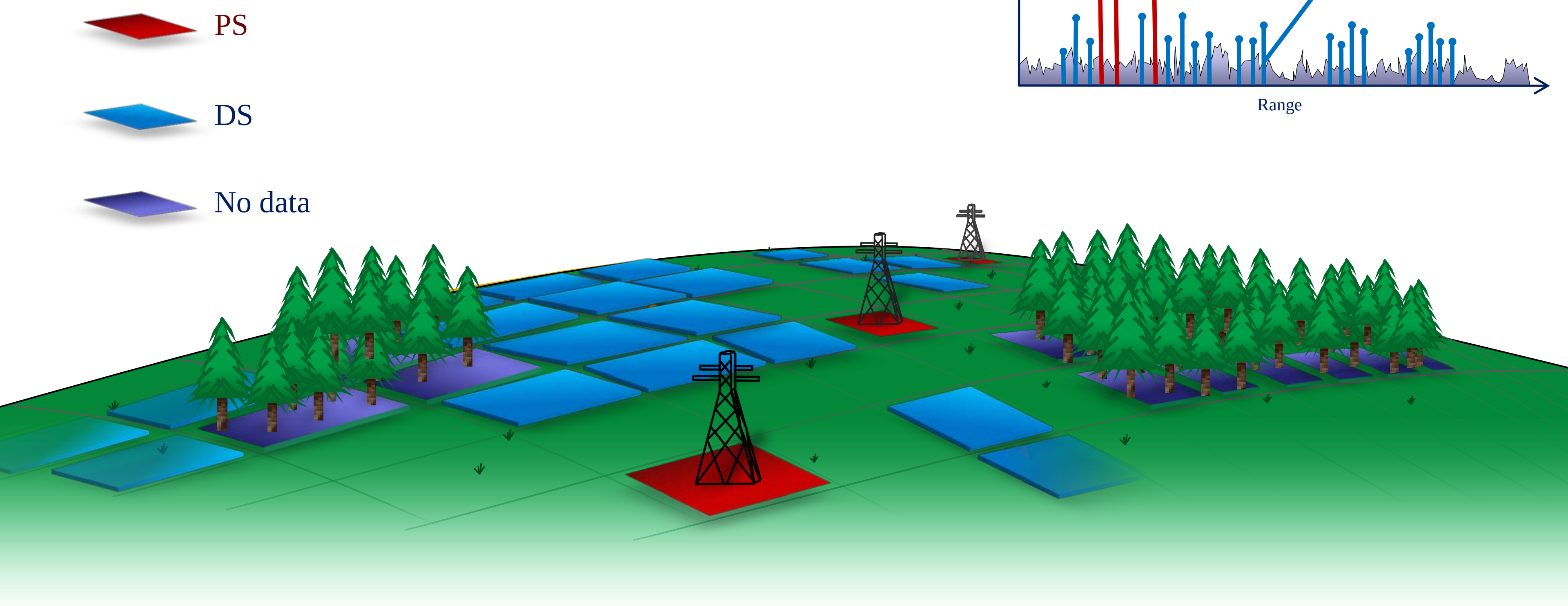
# InSAR Technology: Products

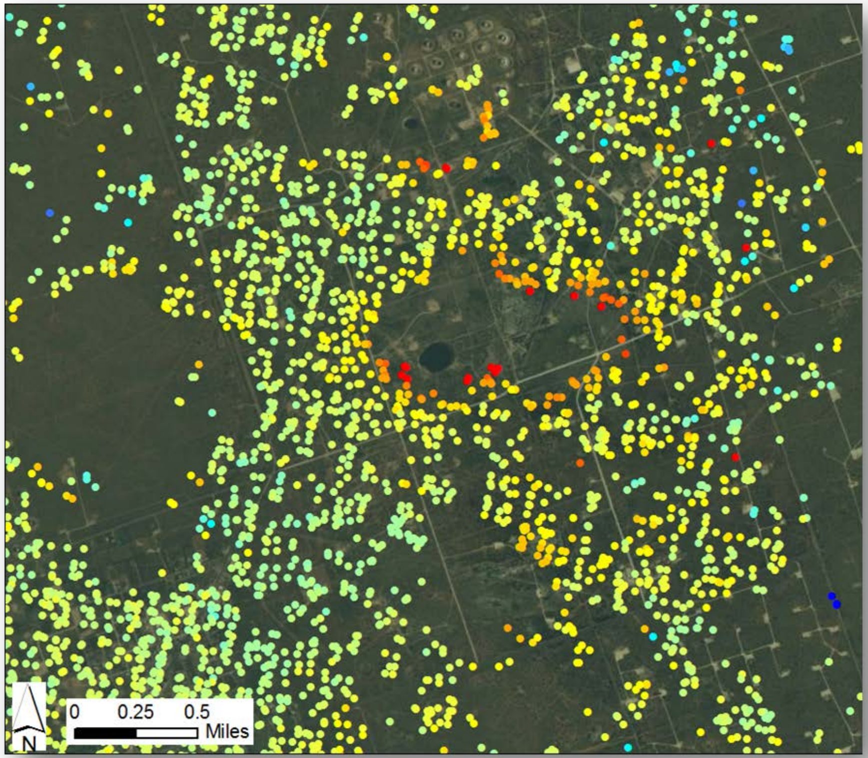
## SqueeSAR™



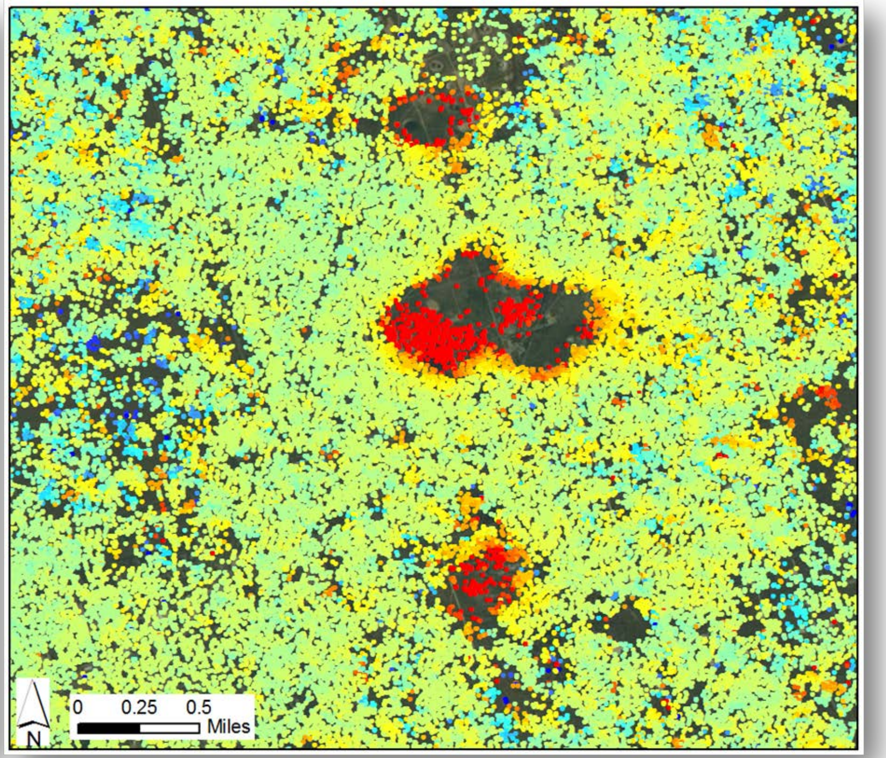



# InSAR Technology: Products

PSInSAR™

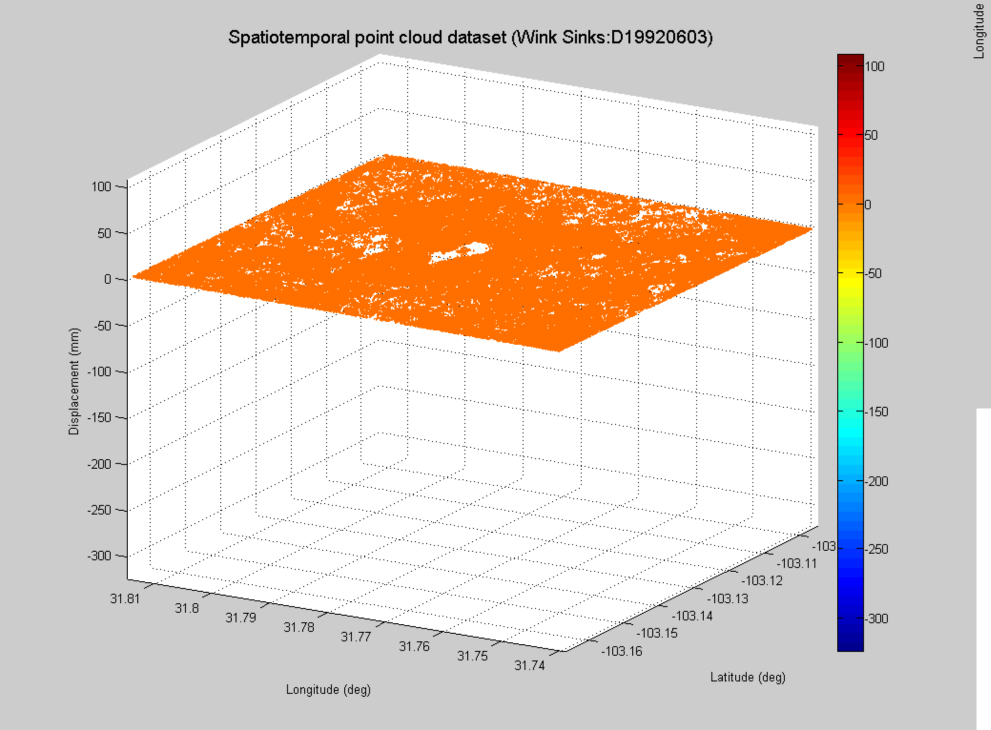


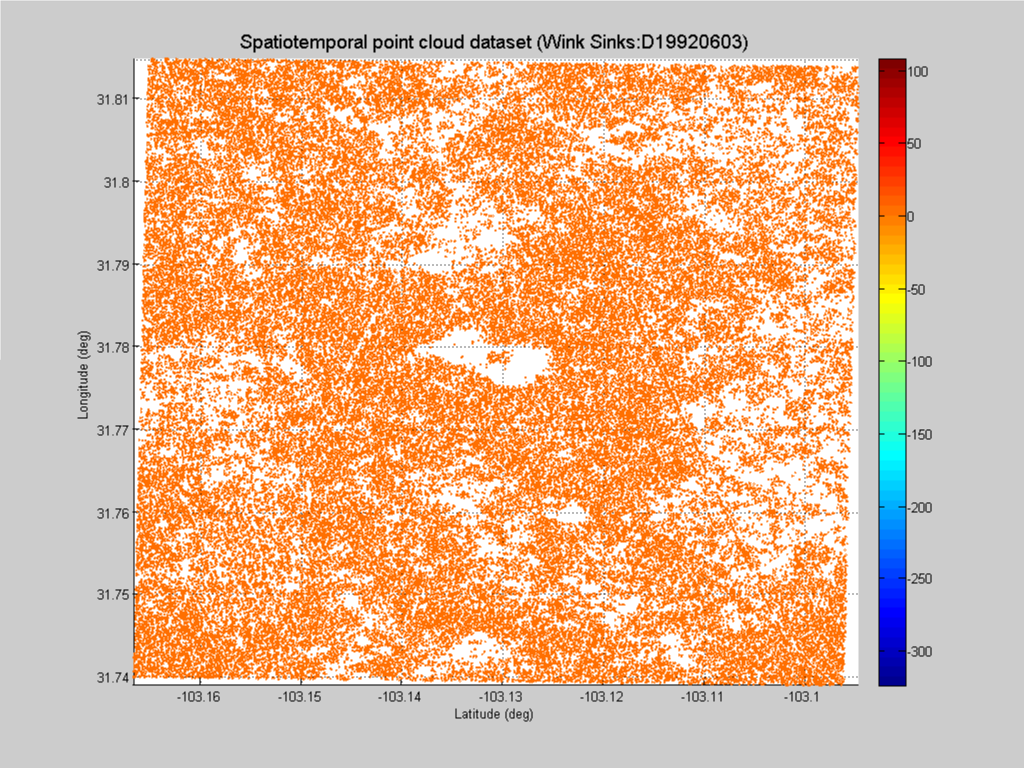

SqueeSAR™



# InSAR Technology: Data sets

Sinkholes



# InSAR Technology

Advantages:

- Active system
- Large coverage in short time
- Short repeat times
- Very high displacement resolution
- Time series of displacements

Shortcomings:

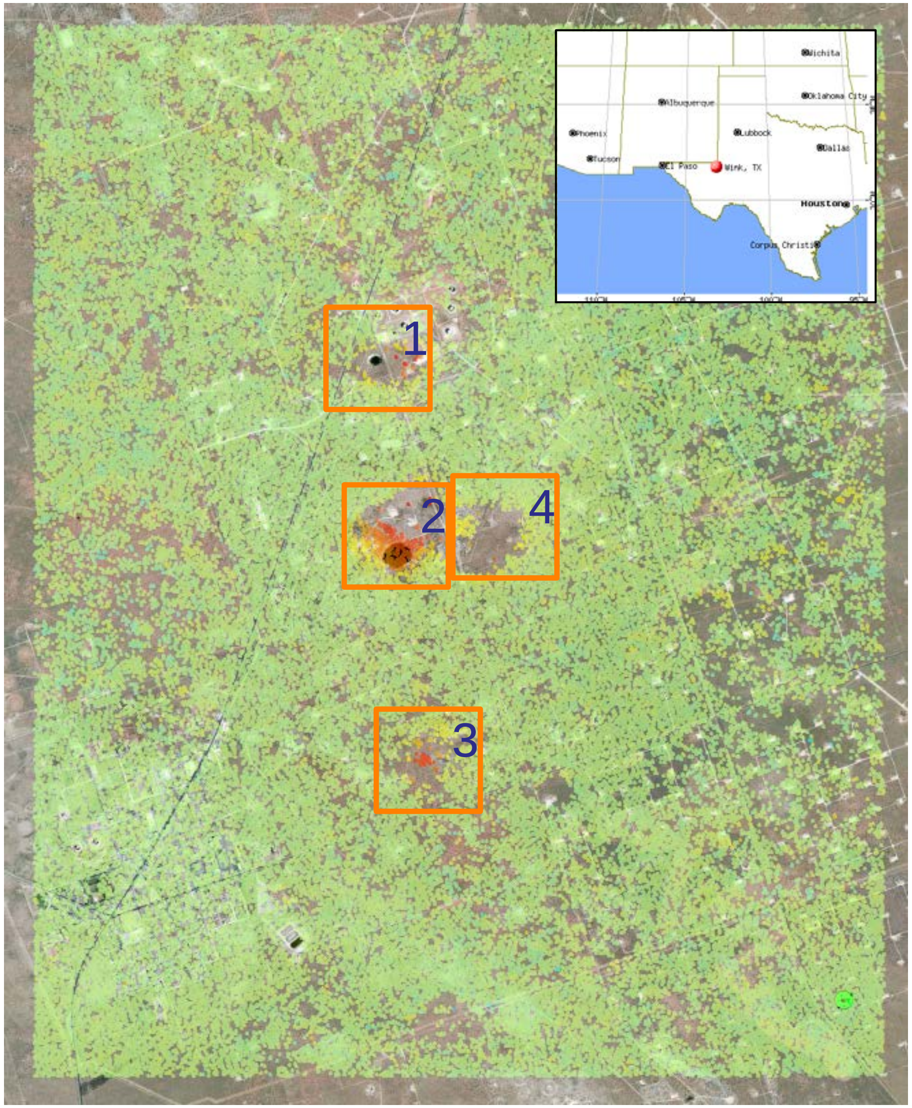
- Moderate starting ground resolution (3x3m)
- Expensive (COSMO-SkyMed: 3600€/scene)

# Modeling phenomena

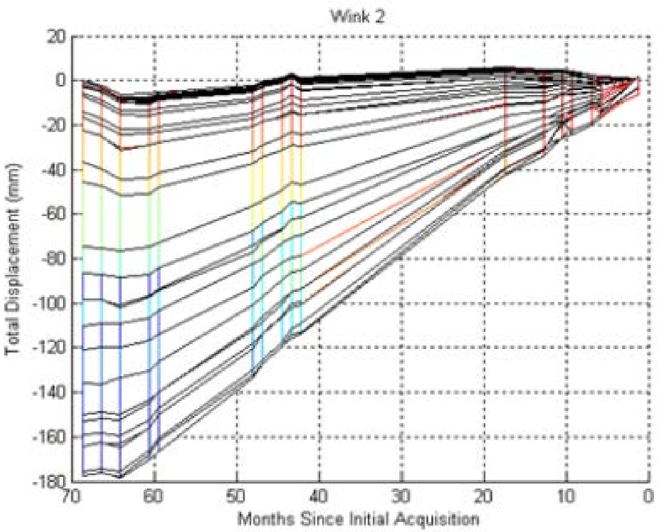
- What is the ground deformation?
- How does it evolve in time?
- Link behavior to underlying geophysics

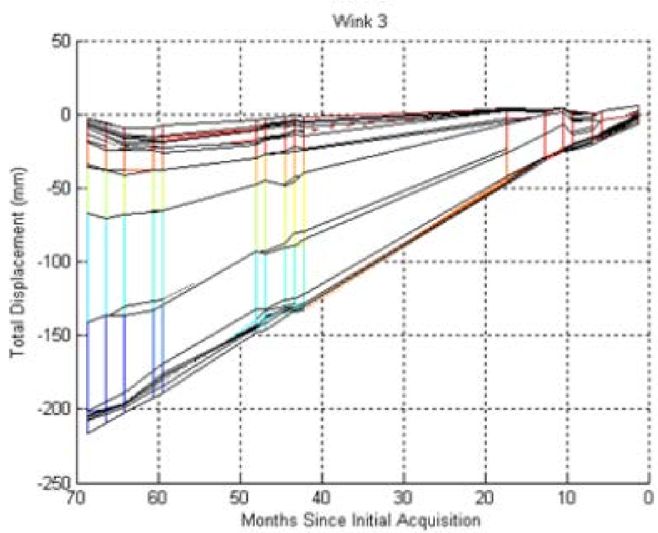
# Sinkholes data set

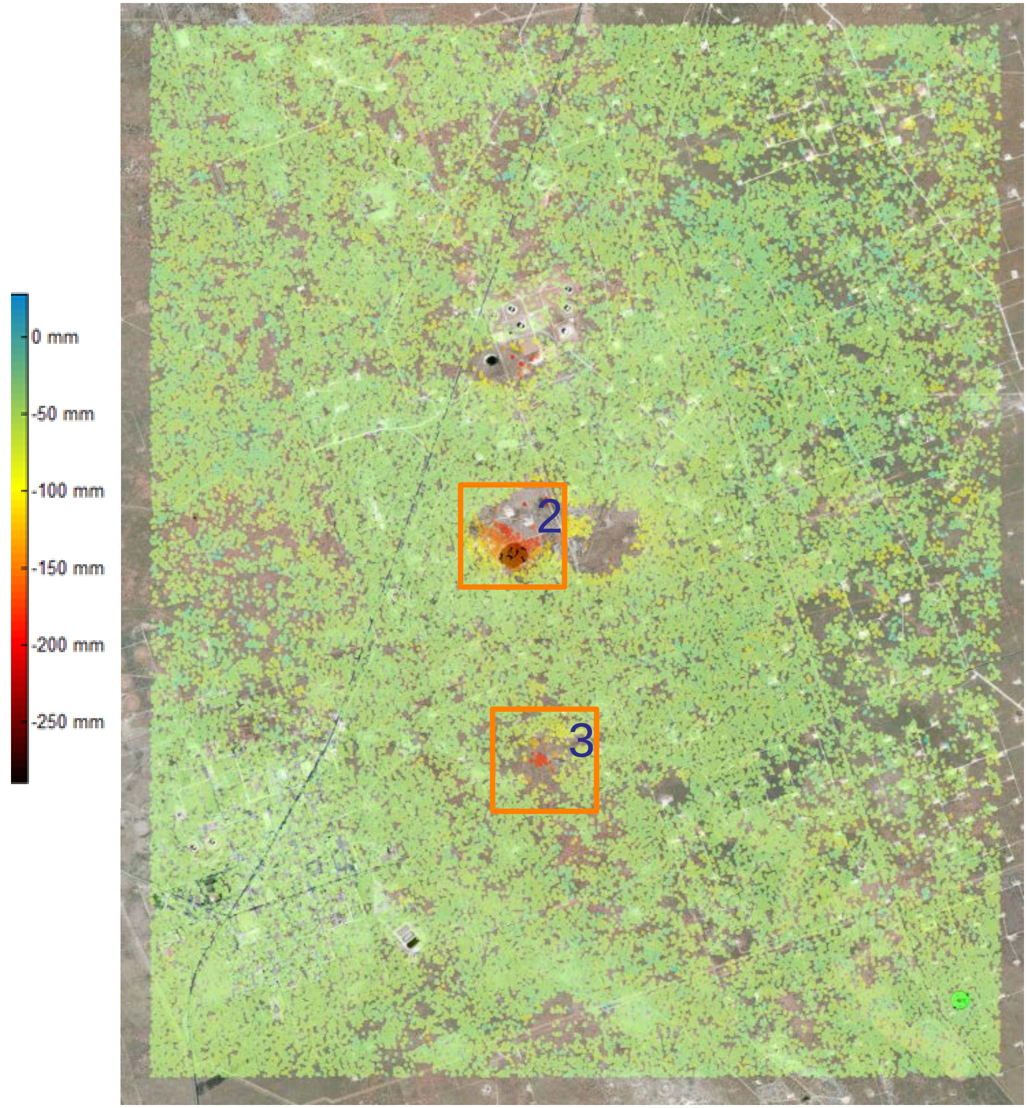
- 93,513 PS+DS points
- 22 Single look complex SAR
- ERS Satellites
- June 1992 to February 1998
- 55km$^2$ near Wink, SW Texas



# Profile extraction

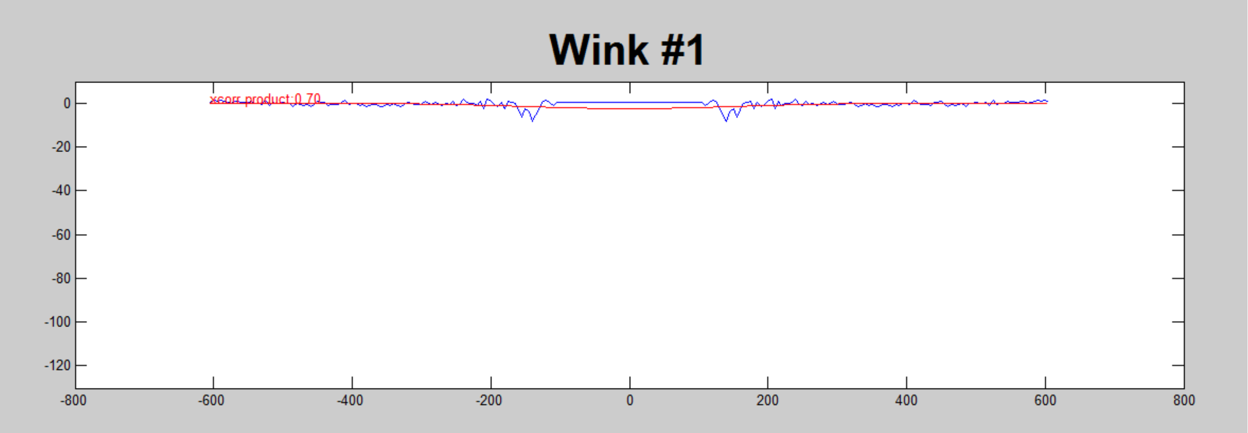


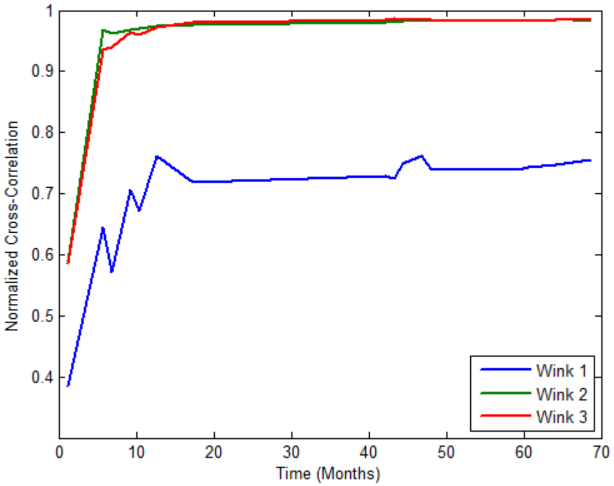



# Spatiotemporal model

Evolving Gaussian? $g_t(x) = \alpha_t \exp(-x^2/2\sigma_t^2)$

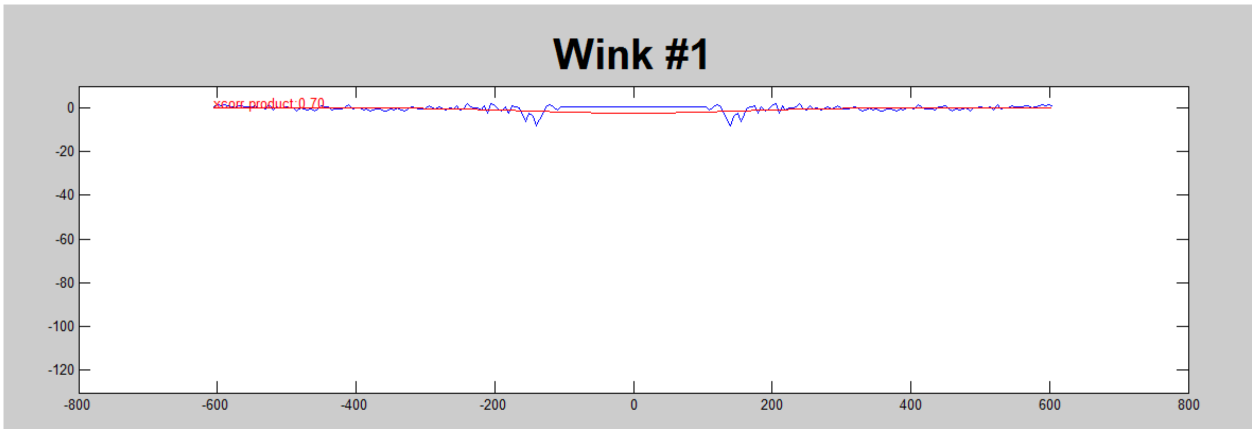


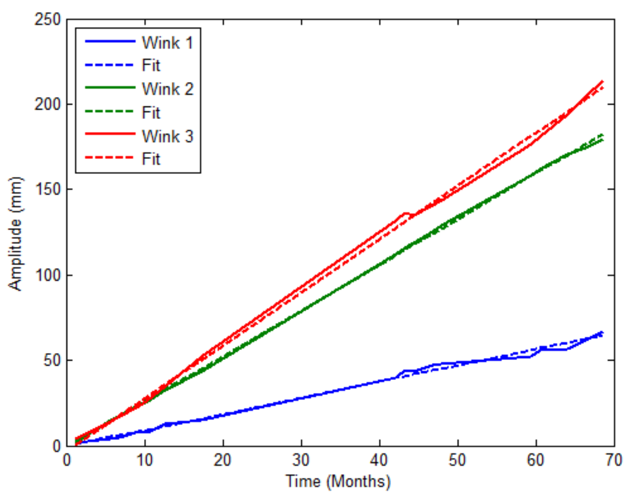



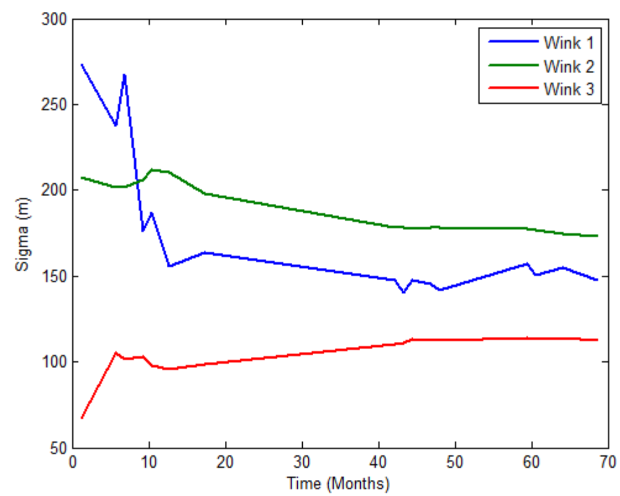
# Spatiotemporal model

Evolving Gaussian!

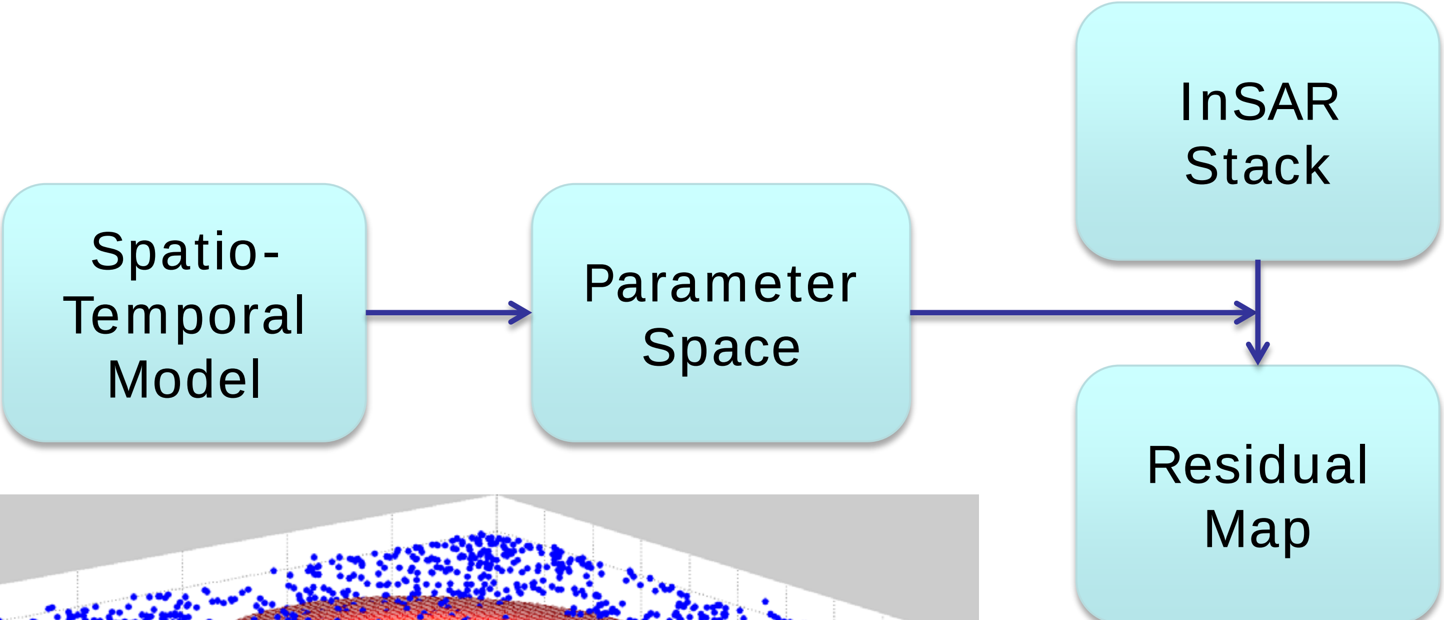
$$g(\boldsymbol{x}, t) = \alpha t \exp[-(\boldsymbol{x} - \boldsymbol{x_0})^2 / 2\sigma^2]$$

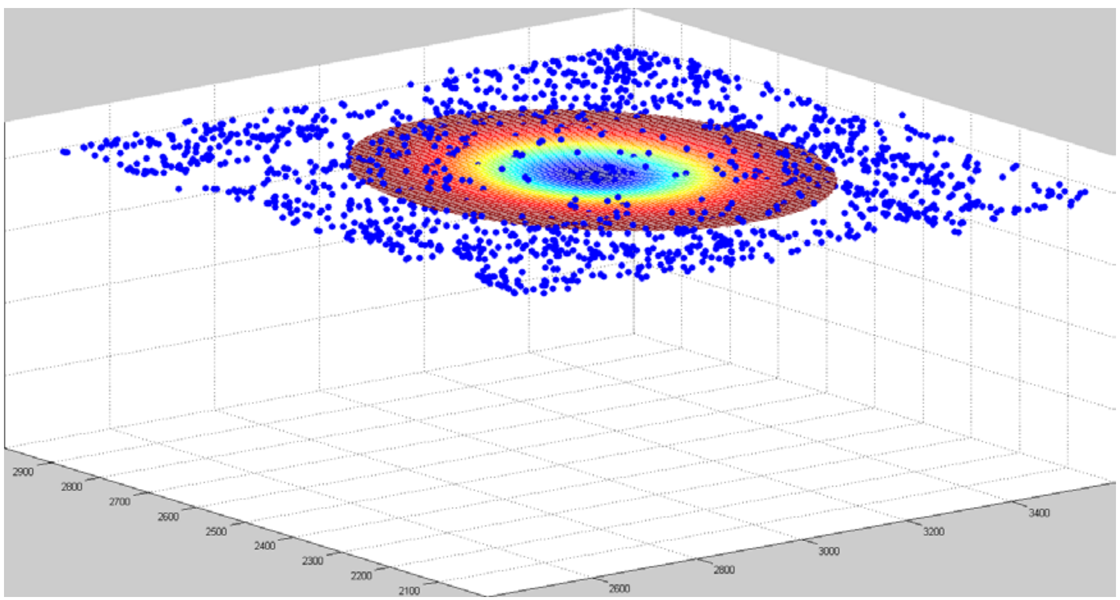


# Feature Tracking: Approach



# Feature Tracking: Theory

$$g_{\boldsymbol{p}}(\boldsymbol{x},t) = \alpha t \exp[-(\boldsymbol{x}-\boldsymbol{x_0})^2/2\sigma^2]$$

Relative residual:

1. Rewrite model in implicit form

$$T(\boldsymbol{x},\boldsymbol{p}) = 0$$

2. Discretize and limit the parameter space $\boldsymbol{p} = [\boldsymbol{x_0}, \alpha, \sigma]$

$$\boldsymbol{p_{min}} \leq \boldsymbol{p} \leq \boldsymbol{p_{max}} \quad \text{with step: } \Delta\boldsymbol{p}$$

3. Define a residual matrix $r(\boldsymbol{p})$ with one element corresponding to each point $\boldsymbol{p}$ in the parameter space

4. For each point $\boldsymbol{p}$ in the parameter space generate the corresponding template $g_{\boldsymbol{p}}(\boldsymbol{x_i},t)$ and define and influence region $R(\boldsymbol{p})$

5. For each data point $\boldsymbol{x_i}$ within $R(\boldsymbol{p})$ evaluate the *relative residual*

$$\mu(\boldsymbol{x_i},t) = \min\left(\frac{\left|d(\boldsymbol{x_i},t) - g_{\boldsymbol{p}}(\boldsymbol{x_i},t)\right|}{\max\left(\left|d(\boldsymbol{x_i},t)\right|, \left|g_{\boldsymbol{p}}(\boldsymbol{x_i},t)\right|\right)}, 1\right)$$

6. Average results within $R(\boldsymbol{p}) \xrightarrow{s.t.mean} r(\boldsymbol{p})$

A. Vaccari, et al. “Detection of geophysical features in InSAR point cloud data sets using spatiotemporal models,” *International Journal of Remote Sensing*

# Validation: Sinkholes data set

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- 22 Single look complex SAR
- June 1992 to February 1998
- ERS Satellites
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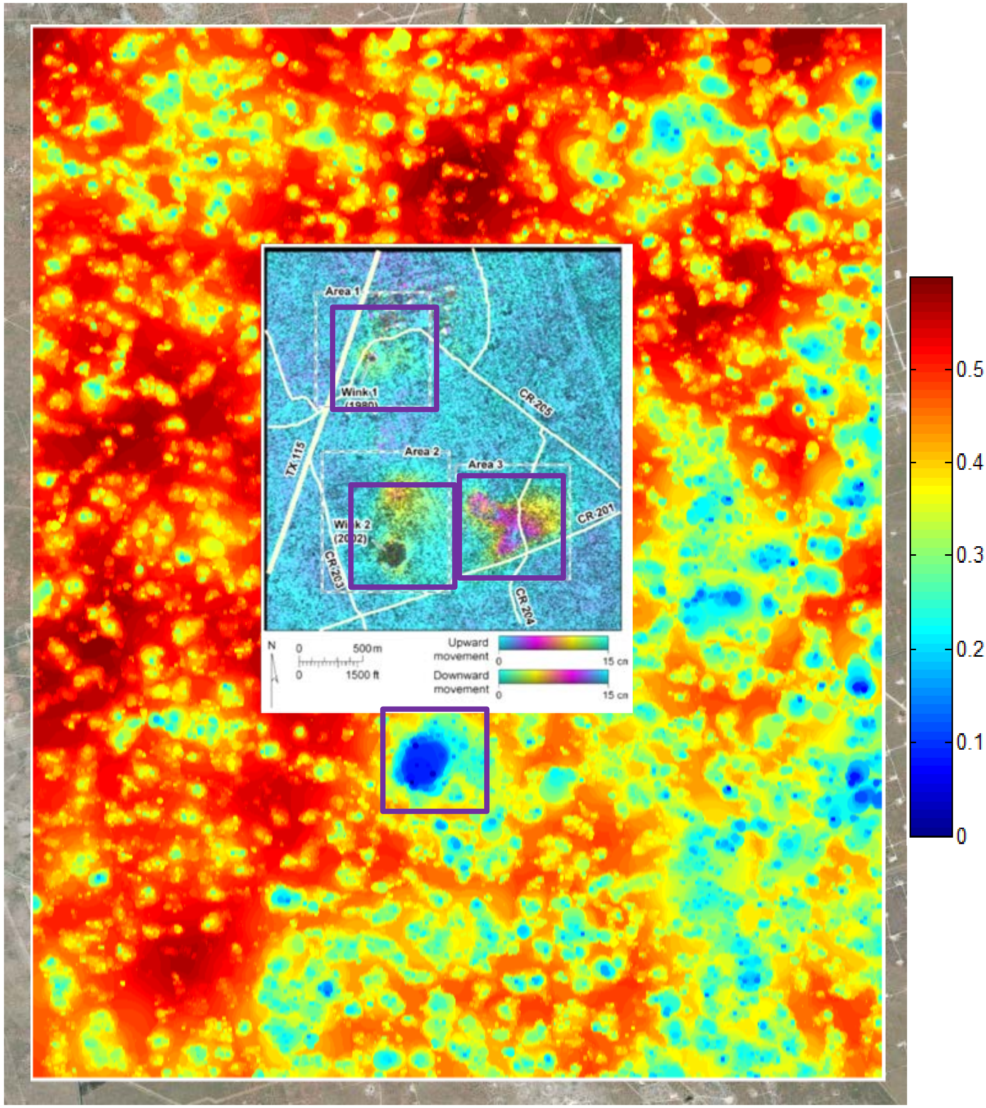
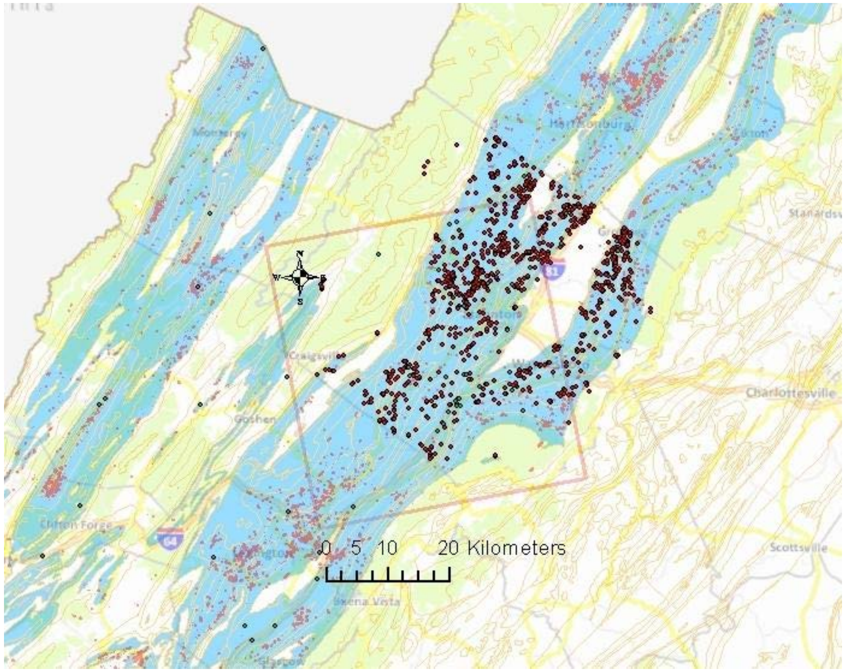
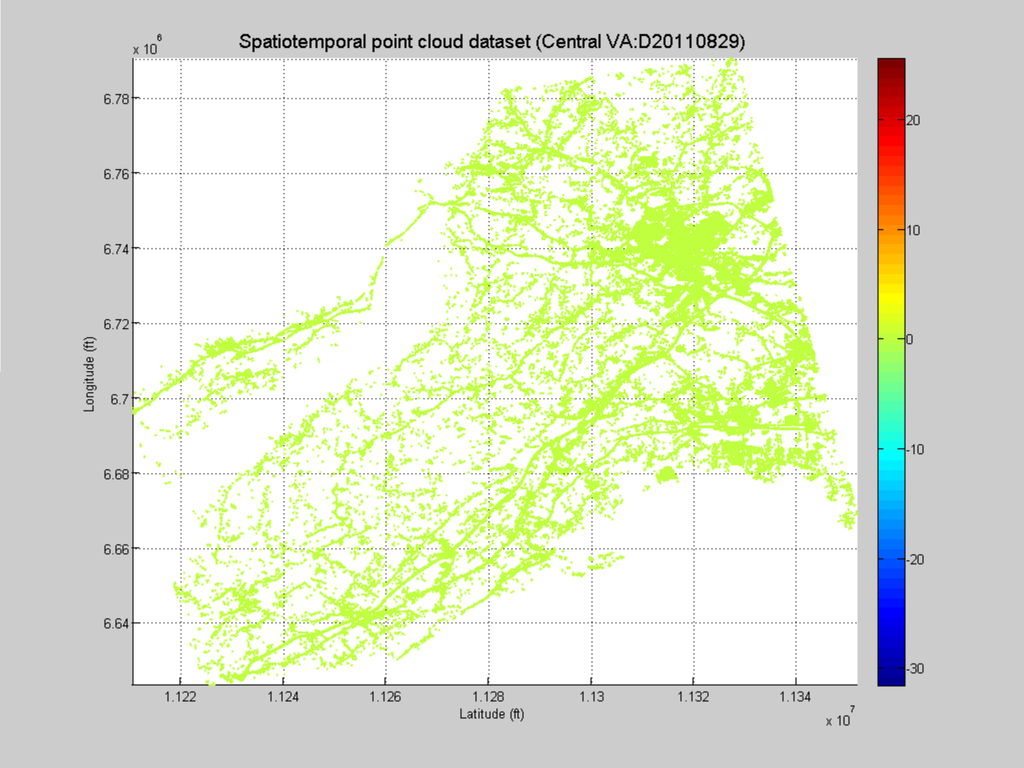


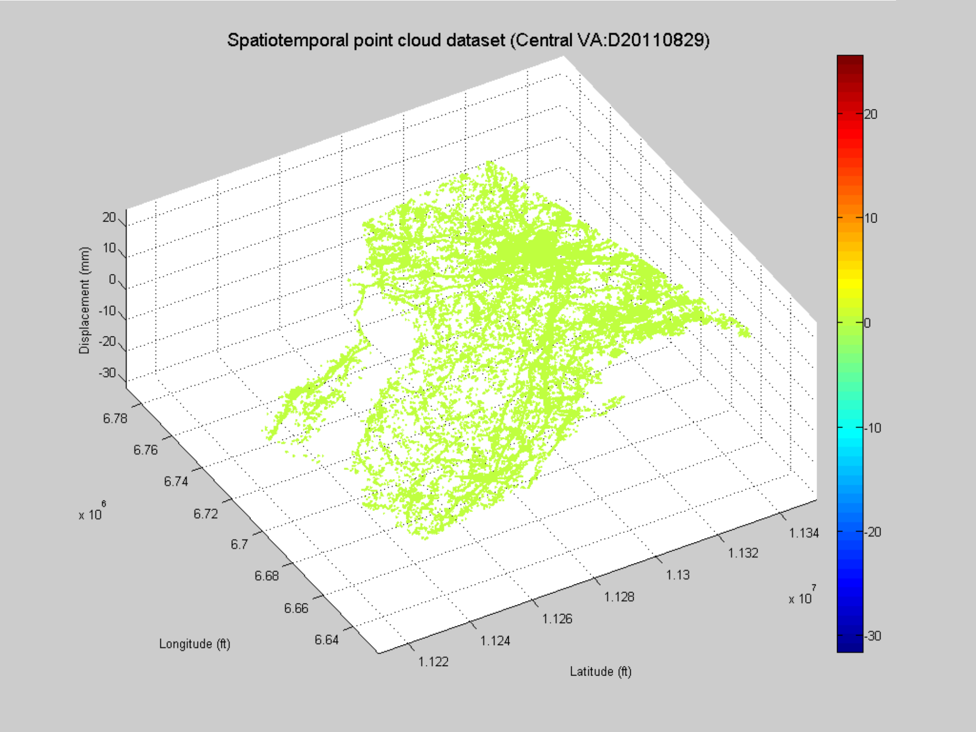
# Central Virginia data set

- 166,348 PS + 129,773 DS
- 32 Single look complex SAR
- August 2011 to October 2012
- COSMO-SkyMed Satellites
- 40x40km$^2$ Augusta County, VA
- USDOT RITARS-11-H-UVA

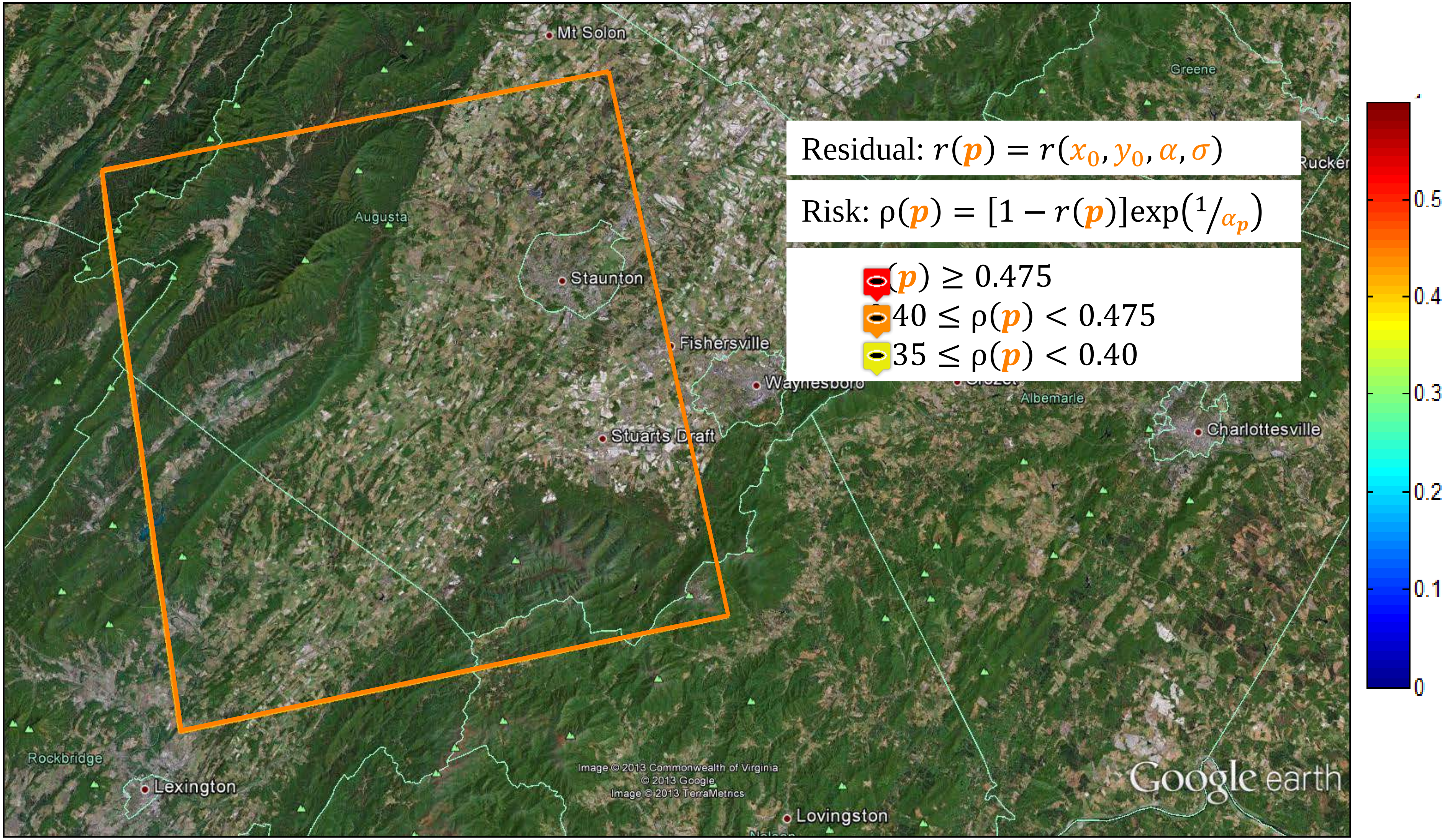


# Central Virginia data set



# Central Virginia data set



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# Central Virginia data set

Credit: Brian Bruckno, Ed Hoppe, VDOT, VCTIR

| Categories | Infrastructure | Geomorphology |
|---|---|---|
| Absolute (A) | Cracks, settlement | Recent non-vegetated scarps |
| Strong (S) | Distortions or cracks | Overgrown scarps |
| Weak (W) | Repairs or cracks | Geomorphology indicates activity |
| Possible (P) | Near existing active region | In correct terrain, presence of pinnacles |
| None (N) | No or negative confirmation | No or negative confirmation |

| Risk | Evaluated | A | S | W | P | N |
|---|---|---|---|---|---|---|
| Severe | 7 | 4 (57%) | 2 (29%) | - | - | 1 (14%) |
| Moderate | 15 | 8 (54%) | 2 (13%) | 2 (13%) | 1 (7%) | 2 (13%) |
| Slight | 10 | 5 (50%) | 4 (40%) | - | 1 (10%) | - |
| *Total* | *32* | *17 (53%)* | *8 (25%)* | *2 ( 6%)* | *2 ( 6%)* | *3 (10%)* |

*25 (78%)*

# Extension to different models

- Extensible method
- Feature tracking
  - Spatio-temporal model
  - Model parameters
- Risk assessment
  - Based on residual map
  - Allow inclusion of external knowledge

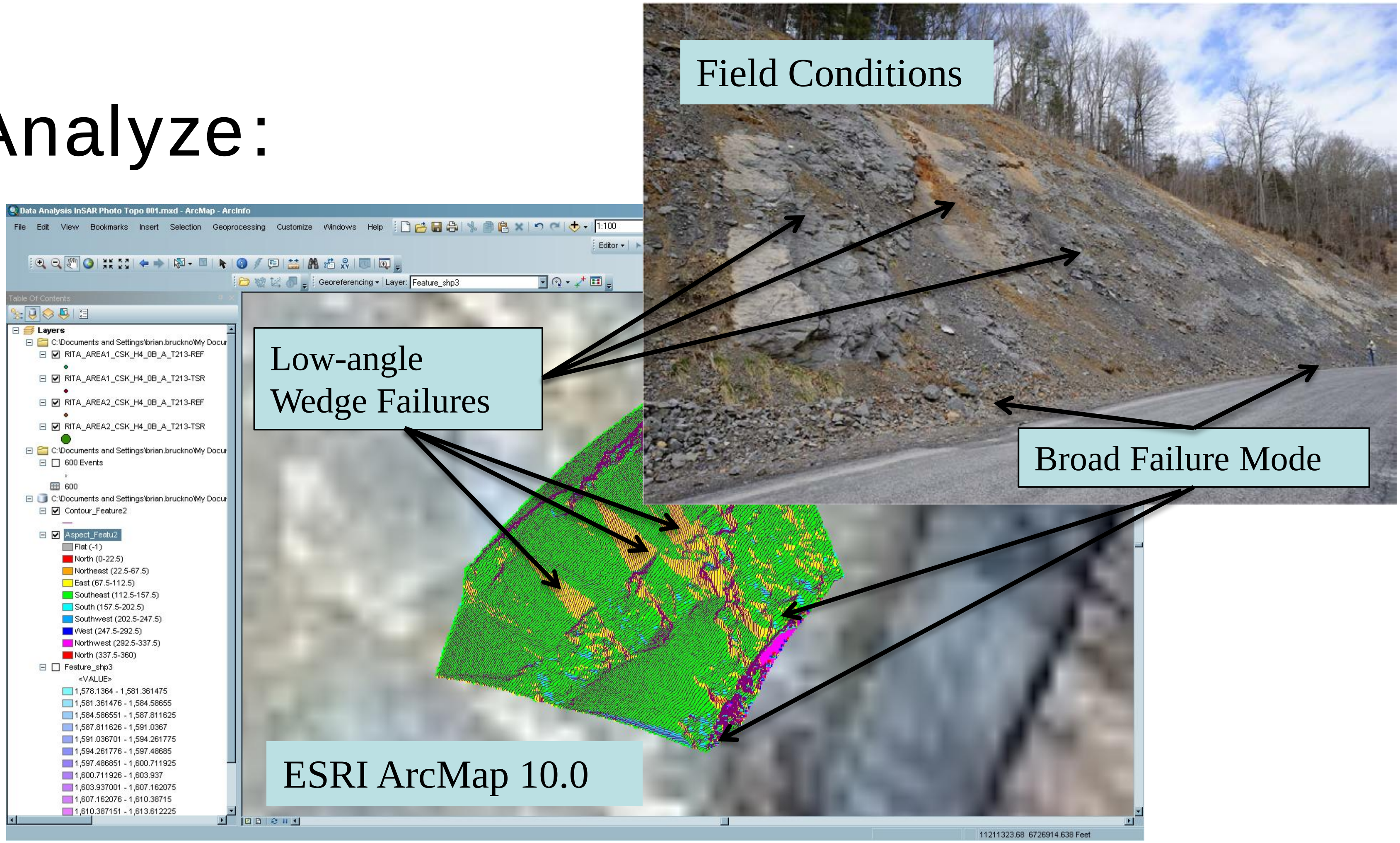
# Field Validation: Vesuvius Sinkhole

## Credit: Brian Bruckno, Ed Hoppe, VDOT, VCTIR

# Field Validation: Vesuvius Sinkhole

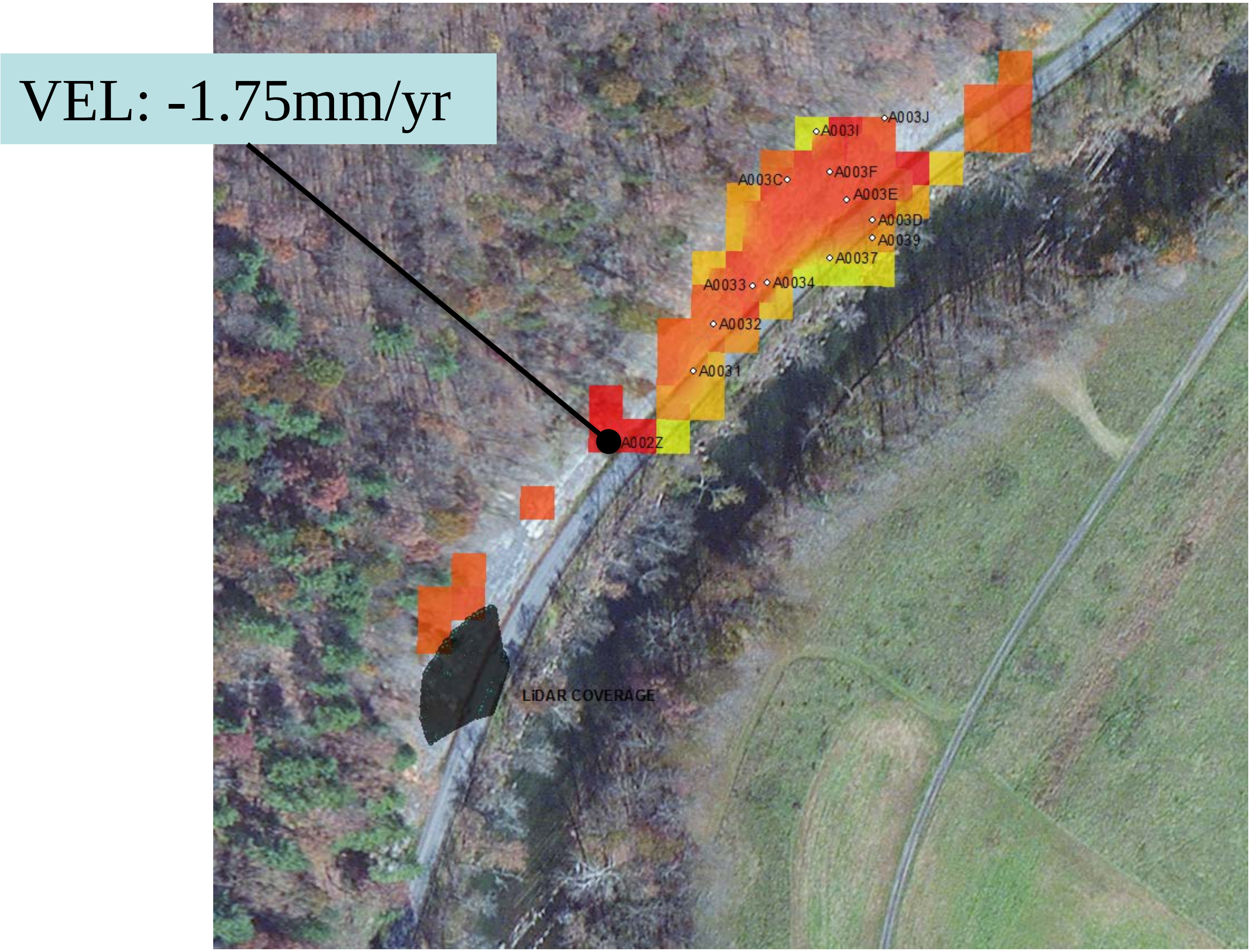
# Field Validation: Rock Slopes

## Analyze:



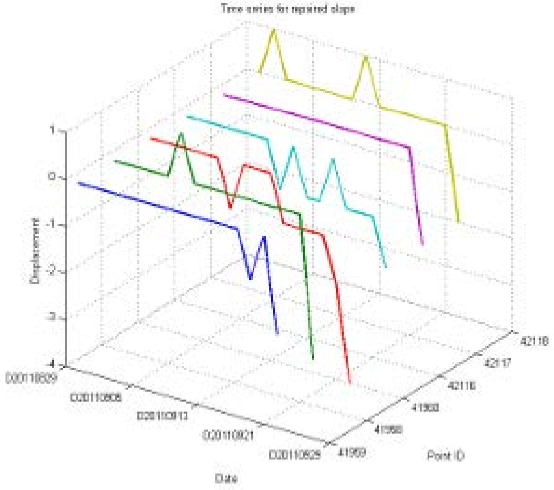
# Field Validation: Rock Slopes

Confirmed:



# Field Validation: Rock Buttress Stability

## Field Validation of InSAR Data:

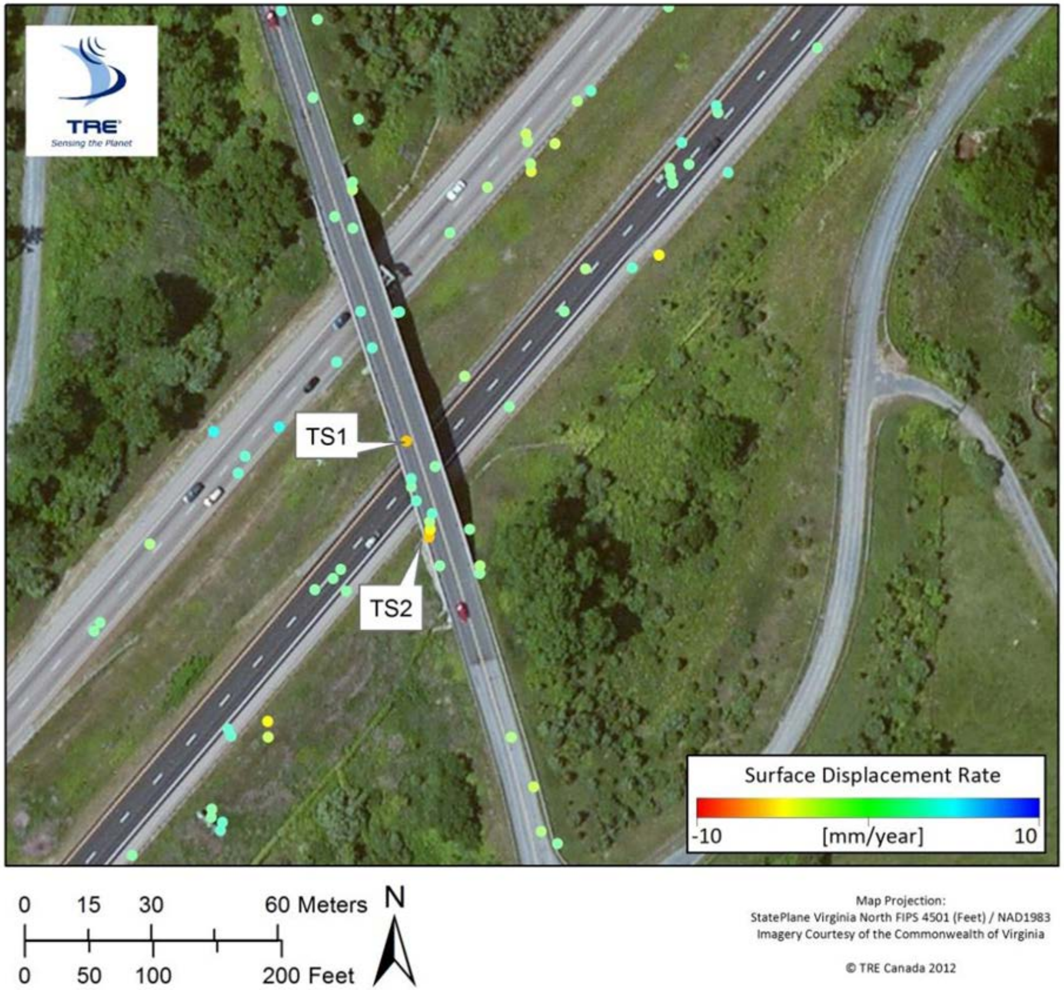



Temporal series of scatterers subset

# Field Validation: Rock Buttress Stability

Field Validation of InSAR Data:

# Field Validation: Bridge on Route 635 over I-81

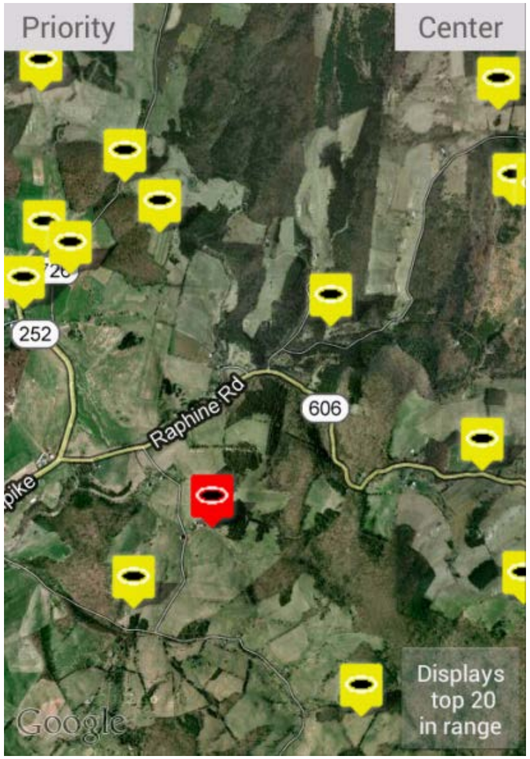


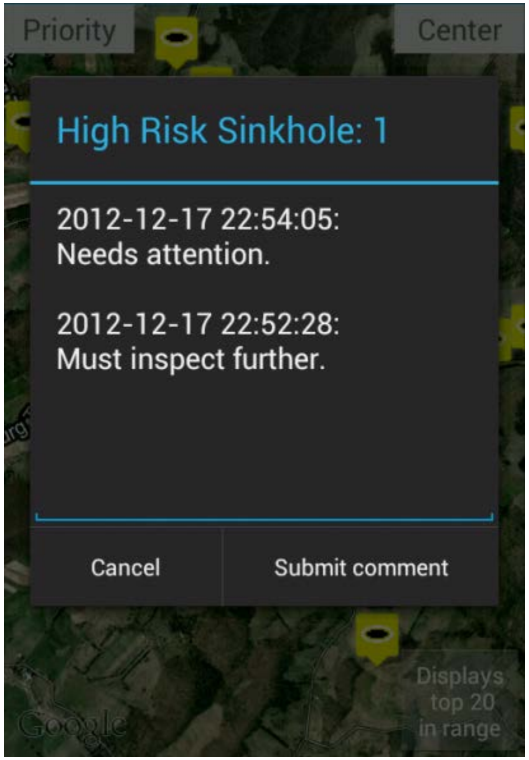
# Field Validation: Bridge on Route 635 over I-81

# Field Validation: Bridge on Route 635 over I-81

# Mobile Devices Deployment

- Proof of concept
- LAMP (Linux, Apache, MySQL, PHP) server
- Real time database query and update
- Google Maps API



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# Project: Future Work

- Extend tested sinkhole algorithm (e.g. bridge and landslide spatio-temporal models)

- Develop pavement condition index based on temporary scatterers

- Develop Risk mapping algorithm based on existing and learned data

# Thank you!